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‘A Laboratory of Heating and Ventilation’: the Johns Hopkins Hospital as Experimental Architecture, 1870-90

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Abstract

This article offers a fresh look at the origins and environmental design of the Johns Hopkins Hospital, Baltimore, between c. 1875 and 1890. It augments existing histories through close reference to the hospital archives and by contextualising the building within the career and interests of John Shaw Billings, a doctor who was retained by the hospital Trustees as an expert adviser on hospital design and management. The episode is presented as one of architectural ‘experiment’, in which a hypothesis was formulated, constructed, and monitored in use. Architecture emerges from this analysis as an act of exploration and position-taking, with the hospital conceived as a ‘tool’ for didactic demonstration in an on-going multi-disciplinary, international discourse concerning the ventilation of non-domestic buildings.

Keywords

Environmental design history, ventilation, hospitals, experiment, discourse

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‘A Laboratory of Heating and Ventilation’: the Johns Hopkins Hospital as Experimental Architecture, 1870-90

Writing to the Trustees of his Estate in March 1873, the Baltimore entrepreneur and philanthropist Johns Hopkins (1795-1873) suggested that the hospital which he had founded should, in its ‘construction and arrangement, compare favourably with any other institution of like character in this country or Europe’.¹ To this end, the Trustees asked five experts on hospital design and management to submit proposals for the new institution.² The publication of the experts’ responses reflected the Trustees’ belief that they had been given ‘a valuable mass of information’ that deserved dissemination.³ The Trustees originally intended their architect, J.R. Niernsee (1814-85), to amalgamate the best features of the schemes. However, one of the competitors, John Shaw Billings, went on to assume a significant role in the realisation of the hospital. Billings (1838-1913) was a doctor who served in the Union Army during the American Civil War before taking charge of the Library of the US Surgeon General’s Office, which he expanded significantly, also creating a comprehensive catalogue of its holdings.⁴ He was engaged by the Trustees in June 1876 on the basis that advice from a ‘medical man’ might be helpful.⁵ Billings had already demonstrated an interest in ventilation and design, and he grasped the opportunity to contribute. Noting that engineers were often biased in favour of particular devices or systems, he expressed the hope that finally, perhaps, this building might settle what he termed the ‘vexed’ question of how to achieve good ventilation in institutional architecture.⁶ In this respect, it was to be what Billings called ‘a sort of laboratory of heating and ventilation’.⁷ Billings’ choice of words was echoed by the *Transactions* of the Royal Institute of British Architects, which recorded after a visit to the newly completed hospital in 1890 that ‘Many of the arrangements [...] have been contrived with a view to instructional purposes. The hospital is a great laboratory for teaching the practical application of the laws of hygiene to heating, ventilation, house drainage, and other sanitary matters.’⁸

The Johns Hopkins Hospital was heated and ventilated by a complex system in which air was ducted through the building by largely passive means, with fundamental effects on the hospital's plan, section and appearance. Wards were laid out as separate buildings (or 'pavilions') to ensure cross ventilation, with in the main one ward per pavilion set on a raised level above a ground-floor 'ventilating chamber' (**fig. 1**). Stacks to exhaust air from the wards were ranged along the roofs above red-brick and stone elevations (**fig. 2**). The inlets and exhausts could be adjusted by means of lever-operated valves according to the season and the degree of ventilation and heat required.

This article develops the idea of the 'laboratory' to shed new light on the particular case of the Johns Hopkins Hospital and also to contribute to the history of nineteenth-century environmental design. Recent work in this area has usefully moved beyond the technological focus of earlier studies, not least by conceptualising the subject in analytical terms as one of experiment in which hypotheses about heating and ventilation were tested in use.⁹ In developing these approaches, I also draw on historians' attempts to conceive buildings in terms of discourse by proposing the design – both in evolution and as built – as an example of position-taking. Architecture emerges not as a finished object but rather as something more provisional, namely the exploration of an idea in built form. This exploration takes place both in the original construction and then in the refinement of the idea through the tuning (or reconstruction) of the environmental strategy. In presenting the Johns Hopkins Hospital in this way, this article augments existing accounts of the building,¹⁰ seeing it less through a typological lens and rather as a well-documented essay in heating and ventilation design. Indeed, Billings' status by the 1880s as a leading authority on this subject has been recognised,¹¹ and so the article contextualises the design by reference to his writings, particularly his numerous unpublished reports for the Trustees, which include apparently hitherto unstudied data on the building's performance. Nonetheless, in practice the hospital was the product of collaboration: the engineers T.J. Hayward and C.W. Newton of Bartlett Robbins and Company, Baltimore,¹² and the Trustees' architects, first Niernsee and later Cabot and Chandler of Boston, also played important if not always well-defined roles.¹³ The first part of the article considers the idea of architectural experiment,

while the second section discusses briefly the significance of ventilation in nineteenth-century hospitals. We then turn to the Johns Hopkins Hospital itself.

Experimental architecture

There is a longstanding relationship between architecture and experiment, from buildings which facilitated scientific work (such as Christopher Wren's Monument in London)¹⁴ to structures erected to test concepts and techniques. Experiment and demonstration, implicit in Billings' idea of the laboratory, were especially fundamental to the environmental design of major nineteenth-century non-domestic buildings. For example, following the destruction by fire in 1834 of the House of Commons in London, the committee charged with reconstruction stated of the heating and ventilation that 'whatever system is adopted, it would be more satisfactory that it should be tested by experiment as nearly as possible, under the conditions in which it would be practically executed.'¹⁵ Under the direction of David Boswell Reid, Lecturer in Chemistry at Edinburgh, a 'model House of Commons, in which experiments [...] might be tried' was constructed and then adapted for the temporary Commons chamber,¹⁶ the performance of which was recorded in detail.¹⁷ Reid's final scheme proved problematic and remedial measures were necessary.¹⁸ However, such alterations to buildings in use were not uncommon. For example, John Shaw Billings was consulted regarding attempts to improve conditions within the US House of Representatives.¹⁹ Meanwhile, in a recent account of the 1851 Great Exhibition Building in London's Hyde Park, Henrik Schoenefeldt has shown how temperatures in Joseph Paxton's glass and iron structure were systematically monitored, with amendments being made to alleviate the overheating that was experienced.²⁰ The value of Schoenefeldt's account lies not solely in its presentation of the vast archive of temperature records but also in its analysis of a structure that has achieved a semi-mythical status in accounts of the so-called pioneers of the Modern Movement. What has often been treated as a completed object emerges as the product of adaptation; indeed, its subsequent history was characterised by an on-going process of environmental adjustment. As the

experience of contemporary low-energy architecture also suggests, fine-tuning and modifications are perhaps inevitable in buildings without the ‘guaranteed’ conditions that can be achieved by mechanical and electrical systems.²¹

Although records of the monitoring of the Johns Hopkins Hospital are relatively brief and suggest that the exercise was never as systematic as that of the 1851 Exhibition Building or Parliament (and was probably more typical in that respect), greater evidence survives of the pre-construction discussions of environmental strategy and the evolution of the executed design. The idea of experiment seems to have been shared by the Trustees and Billings. For example, the President of the Trustees wrote that ‘there must be some general principles of hospital hygiene and of hospital treatment fixed and immutable in their character, the discovery and proof of which are the result of close, careful recorded observation and judgement.’²² Billings, meanwhile, was reportedly a fan of experiments. His biographer records that on being told that the surgery that he had received for cancer was partly for ‘experimental purposes’, he apparently ‘cheerfully submitted to the pain and said no more about it.’²³ During his medical education he was reputed to have spent little time in lectures, preferring the practical world of the laboratory.²⁴ Information-gathering was also a theme in his work: as well as overseeing the expansion and cataloguing of the Surgeon General’s library, he published a major report on US Army barracks (1870) which relied on material collected in the field, and he consistently stated the need for solid facts rather than general remarks.²⁵ He applied the same kind of exploratory approach to the Johns Hopkins Hospital. First came a review of current practice on the basis of the literature and visits; there were also specially commissioned experiments. There then followed a hypothesis, which ultimately manifested itself as the final design of 1877-78. Finally, the experiment was constructed – quite literally – and examined to see how it performed.

That a doctor might seize particularly on the hospital as the venue for personal experiment is not a new argument, at least as far as it relates to patient care. Adrian Forty has argued that the hospital functioned during this period increasingly to classify the sick, with ‘patients’ being not clients but

rather the recipients of care.²⁶ Their doctors were thus placed in a position of control. In this way, Forty suggests that the hospital allowed doctors the opportunity to cement their own status through investigation and experimental treatment. It is not a great leap to treat a hospital building as the object of experiment, or at least didactic demonstration. Several historians have outlined the interest of doctors and nurses in building design in this period. Cynthia Hammond, for example, has discussed Florence Nightingale's position during the 1860s as an influential advocate of the pavilion-plan hospital, noting her role also as an occasional designer.²⁷ Annmarie Adams has shown how nineteenth-century doctors critiqued domestic architecture and proposed their own solutions.²⁸ In essence, buildings could be likened to a living body which could be cured.²⁹ For example, during the eighteenth century, Stephen Hales had presented a ventilator made of two pairs of bellows.³⁰ Hales suggested that the application of these lung-like ventilators turned the hospital – an inherently 'unnatural' building type – into something that could potentially be returned to nature.

If architecture is conceived less as a fixed entity and more as an exploratory or experimental vehicle we might further consider it in terms of discourse, or the taking and defending of positions. It has long been recognised in architectural history that buildings may be shaped by exchanges of ideas and that an understanding of these ideas, as expressed in texts and other sources, can usefully contextualise designs. Historians such as Sarah Williams Goldhagen have extended that view to present buildings themselves as contributions to discourses.³¹ Architecture is thus conceived as a kind of position-taking, as much as being an end in itself. The relevance of this idea to hospitals is evident in Christine Stevenson's suggestion with reference to the eighteenth century that 'the presence [...] of new hospital buildings fed into new ways of showing them, of writing about them. These **demonstrations** [my emphasis] were, however, [...] complex'.³² Although the Johns Hopkins Hospital functioned as a clear 'demonstration' of Hopkins' own philanthropy, its environmental strategy was also placed on clear view. The prominent display of exhaust stacks at roof level and the exhortation of the official hospital guide that visitors should 'note mixing valves in walls at head of beds for regulating temperature of fresh air supply without interfering with quantity'³³ both

demonstrated the importance attached to the movement of air through the building and its place within an international discourse relating to the ventilation of hospitals and other complex non-domestic buildings.

‘Dangerous impurities’

Ventilation was a significant topic in nineteenth-century architecture, out of concern for public health rather than more mundane questions of comfort. Miasmatic theory held sway in the early part of the century, proposing that the air was corrupted by the exhaled products of humans and animals, and by decaying organic matter, with this corruption being revealed by bad smells. The resulting miasmata were not simply like poisons; rather, they were poisons that led to illness. These ideas were especially relevant in hospital design. The buildings in which the sick were housed had long been thought often to worsen their condition.³⁴ Ventilation was recognised as one way of ameliorating the situation, and the subject was well-established in discussions of hospital architecture.³⁵ However, it assumed particular prominence during the late 1850s, first in several articles in *The Builder* and then in Florence Nightingale’s influential *Notes on Hospitals*.³⁶ Nightingale’s recommendations, based on her experience of British field hospitals in the Crimea, included cross-ventilated, dormitory-type wards arranged as separate pavilions: the aim was to prevent the easy movement of air from one ward to another. These ideas, which drew on established French practice, had a significant influence on hospital planning across Europe, North America and beyond during the second half of the nineteenth century.³⁷

Even as the work during the 1870s of Joseph Lister, Louis Pasteur, Robert Koch and others fostered new ideas of infection transmission, ventilation remained a subject of interest and debate.³⁸ As Nancy Tomes points out, ‘early understandings of the germ, which emphasised its ubiquitous presence in air and water and its hardiness outside the body, neatly harmonized with already accepted modes of protection against zymotic disease.’³⁹ New manuals of design included recommendations relating to ventilation similar to those found in older guides. Indeed, they were given added force by the idea that

ventilation would remove bacterial ‘clouds’.⁴⁰ Thus in Britain *The Builder* continued to feature numerous articles on the subject during the 1870s and 1880s,⁴¹ and the continuing ferocity of the discourse is evident from the strident language used by the competing promoters of patent systems.⁴² Pavilion-plan hospitals, too, continued to be built.⁴³ Billings combined the two understandings of infection transmission in 1875 when he reported that both ventilation and ‘thorough scientific cleanliness’ were fundamental to a safe hospital.⁴⁴ Later, his assistant at Baltimore, Dr Alexander Abbott, was well-versed in contemporary practice yet also apparently did not believe the Johns Hopkins Hospital to be out-dated as he played a key role in collecting the temperature and humidity records of the building,⁴⁵ to the origins and design of which we now turn.

The Johns Hopkins Hospital

In March 1873, Johns Hopkins charged his Trustees with the task of designing and constructing a hospital, envisaging an institution that would ultimately receive around 400 patients. In May 1874, it was resolved to appoint as architect J.R. Niernsee, and it was reported in November that his services had been secured for \$3000 per annum.⁴⁶ Niernsee was prominent in Baltimore and had already worked for Hopkins as well as for the President of the Board.⁴⁷ Particularly relevant was the house at Baltimore that he had designed in the early 1850s with J. Crawford Neilson for Thomas de Kay Winans. Realised with the same engineering firm as the hospital, it demonstrated his experience of organised heating/ventilation systems, with air being extracted from the house via a stack 140 feet (42 m) tall.

The Trustees set out to understand the state of hospital design, visiting examples in New York, Philadelphia, Boston and Washington DC. However, they were reluctant to proceed without technical advice, stating that ‘it is still maintained by a weight of evidence too eminent and too learned to be ignored that reform has not yet gone far enough, and that it yet remains for some institutions, having adequate means at command, to carry the improvement to its highest capability.’⁴⁸ Suggesting that they did not ‘feel

justified in attempting to cope, unaided, with a technical scientific question',⁴⁹ the Trustees settled on their plan of asking five authors to contribute proposals for the organisation and design of the new hospital. Billings' barracks report clearly qualified him for the task. The others were: Norton Folsom, a doctor at the Massachusetts General Hospital; Joseph Jones, the Professor of Chemistry and Clinical Medicine at the University of Louisiana; Caspar Morris, one of the founders and designers of the Protestant Episcopal Church Hospital, Philadelphia; and Stephen Smith, a surgeon in New York and designer of Roosevelt Hospital. Francis King, President of the Trustees, later emphasised that questions of ventilation and heating were 'certainly not second in importance' among the matters on which the Trustees had sought advice. He asked 'whether ventilation should be accomplished by what is called the natural method, through windows, doors or unavoidable leakages, or through flues and ducts acted upon by the differing temperatures of the outer and inner air, or by enforced currents set in motion by fans, blowers or other mechanical contrivances...'⁵⁰

The resulting essays, published in early 1876, were a review of current knowledge as well as a plan for future action.⁵¹ The authors essentially all proposed pavilion-type hospitals, but there were differences. Folsom suggested wards inspired by the Massachusetts General, i.e., square single-storey pavilions, which Folsom felt resulted in better area and cubic space per bed and achieved good results in terms of heating and ventilation. His advocacy of centralised planning reflected a wider debate which found fruit in a number of European hospitals during the 1880s.⁵² In his scheme, air was introduced at the centre of the ward having been warmed as necessary, before being removed at the perimeter and ducted under the floor to a heated central stack into which there were also openings at ward ceiling level for periodic rapid exhaust.⁵³ Inlet ducts were mirrored to allow for adjustment based on wind direction. Folsom's isolation ward was more conventionally linearly planned, with air entering at the edge and being exhausted at ceiling level. He also included details of a mixing valve that would allow incoming air to be heated as necessary according to the season; he further devised a ventilated operating table. A number of elements of his scheme appear in the executed

hospital, and Billings later illustrated Folsom's switch valve in his book, *Ventilation and Heating*.⁵⁴

Jones' scheme was more obviously in the Nightingale tradition, with linear pavilions staggered along both sides of a spine corridor. Morris criticised forced ventilation and instead proposed wards in which air would be exhausted via the fireplace and via special ducts. Smith advocated permanent pavilions of one storey, with, like Folsom, a large air chamber below each ward. He considered forced systems but ultimately suggested that natural ventilation would yield the best results. Air would be heated if necessary and enter the wards at floor level. Windows were not opposite each other, because Smith thought that staggered windows achieved better mixing of the air, while he also proposed cavity walls in which could be circulated cool or warm air, or disinfecting agents. Meanwhile Billings' proposal drew clearly on Nightingale in its overall plan of parallel pavilions. Each contained one or two storeys of wards, set over an air chamber (**fig. 3**). Air (heated if necessary) was ducted from this chamber into the wards at high and low levels, being exhausted at the skirting to an 'aspirating' stack to which heat would be applied if necessary to guarantee air movement; there was further provision for an exhaust ventilator at the ridge. Individual bed spaces would have their own ventilation controls. Particularly persuasive was the authoritative way in which he described the organisation of the hospital, and his inclusion of information on the existing Baltimore climate. Also notable was Billings' evident knowledge of precedents from America and Europe: he cited examples including Reid's Houses of Parliament and the Winans House.

Though it appears that Niernsee was intended to synthesise the various schemes and that he saw positive features in several of them,⁵⁵ matters changed course when the Trustees asked Billings for assistance. They reported that they had sought 'an adviser possessing comprehensiveness of medical education who had made special study of the subject of hospital hygiene and organisation, and could adapt constructive art to the end proposed, and they have found no-one who unites these qualities in a higher degree than Dr John S Billings...'⁵⁶ Billings accepted the appointment and told the Trustees that he intended to visit European hospitals that Autumn.⁵⁷

During the summer of 1876 he examined Niernsee's plans, reporting in September.⁵⁸ He noted that Niernsee's scheme was not a finalised design, but rather had been submitted for comment, which he was now going to make. Billings reported that he reasonably content with Niernsee's basic plan, including his modification of Folsom's square ward. However, he believed that the ventilation strategy was more problematic. Although Niernsee had drawn on Reid's theories,⁵⁹ Billings thought that what he proposed (which was similar to the apparently successful Winans house) might not transfer well to a large institutional building.⁶⁰ He feared the complexity of Niernsee's ducts might lead the flow of air to stall or to reverse. Billings also thought that the proposed central aspirating exhaust stack might not work with cross-ventilated wards; the air might simply go from the windows to the outlets without mixing. Furthermore, a single exhaust for the whole hospital meant that the wards were essentially all connected, running counter to the separation that was at the heart of Nightingale's theory.⁶¹ Fans might be introduced, suggested Billings, to ensure the correct movement of air, but the effort of using them would be out of proportion to the results obtained.

Billings had an established understanding of hospital ventilation; indeed, Brieger reports that it was 'Billings the man' rather than his scheme which recommended him.⁶² The principal statement of his views at this time was his report on American barracks.⁶³ This publication presented a wealth of information, distilled from proformas that had been supplied to military posts during 1868, the intention being that staff record not only details of the condition of the troops but also details of the buildings in which they were housed. He emphasised that buildings should be designed from the outset to achieve good air change rates, rather than be reliant on ventilators:

'This subject of ventilation is one that has been darkened by a multitude of counsel, and the popular idea of it is that it is to be effected by the use of certain mysterious appliances called ventilators. Those who have made themselves most prominent in connection with this subject are in many cases persons who desire to make money by some patent which is to be a universal panacea, or men zealous, but without corresponding knowledge, who exaggerate the evils of mismanagement as the best means of drawing attention to the subject and to themselves.'⁶⁴

Billings cited approvingly the 1861 report on barrack design that had been circulated in England. He argued that fresh cool air should ideally enter at the

bottom of the room and warm air pass out above. However, while this strategy might introduce sufficient quantities of air, care needed also to be taken to achieve a satisfactory distribution. The openings for fresh cool air should thus be near the ceiling in cold weather, but would be better near the floor when the fires were not in use. Both sets should have tightly fitting doors so that either could be used as required. Meanwhile the exit shaft would be at the top. The ventilation arrangements of 151 US Army posts were then discussed, with measurements showing that many had inadequate ventilation. Special study was made of Army hospitals:

‘As the evils of improper plan and construction are more directly manifest in hospitals than in any other class of buildings, with the exception, perhaps, of prisons, the attention of physicians, engineers, and architects has long been turned to their improvement.’⁶⁵

However, he felt that the majority were deficient. Only that at Willet’s Point fully met his approval.⁶⁶ This building was 75 feet 6 inches (23 m) by 31 feet 6 inches wide (9.6 m) and 50 feet (15.2 m) high, with a cupola. Billings noted that

‘The ventilation of the main ward on the second floor is excellent. There are eight openings at the floor, and the same number at the top of the walls, each being 3 feet 6 inches long by 6 inches high.’⁶⁷

Billings’ sources were, once again, the English Barrack Commissioners, as well as *Notes on Hospitals* and Reid.⁶⁸

The Johns Hopkins Hospital as built reflects an evolution of Billings’ initial submission combined with elements of Folsom’s scheme, in particular. Its development was informed no doubt by consultation with the engineers and architects as well as further analysis and reflection, in which Billings played a central part. In late 1876, he corresponded with Florence Nightingale,⁶⁹ as well as making the trip to Europe that he had promised the Trustees. His letters attest to the places he visited.⁷⁰ In London he saw the Nightingale pavilions at St Thomas’ Hospital, then under construction. Visits followed to Oxford, Cambridge, Berlin, Dresden, Vienna, Paris and Edinburgh, where he met Lister. Yet his conclusions were ambivalent:

‘I do not think we have much to learn from Europe as regards the general principles of hospital construction and management, or as regards methods of heating and ventilation, in fact these things cannot

be said as yet to be settled on any scientific basis of observed facts and there are nearly as many opinions as persons.’⁷¹

Reporting in January 1877, he offered a discussion of different approaches to ventilation, namely, whether air should be propelled into wards or extracted from them. He then returned to his criticism of Niernsee’s ventilation, proposing on the basis of European and American practice a separate exhaust for each pavilion rather than the central exhaust of Niernsee’s scheme.

By the end of the year Niernsee had resigned.⁷² His reason for leaving is not clear: did he fall out with Billings? There are subtle criticisms of Billings in Niernsee’s report to the Trustees,⁷³ while, as has been noted, Billings was critical of Niernsee’s approach to ventilation. Billings had a reputation as someone not altogether easy to get on with, though Niernsee had at least the advantage of his gender, for it was later reported that ‘women would have liked [Billings] if he gave them the chance. He didn’t.’⁷⁴ Nonetheless, Niernsee remained a frequent visitor to the construction site until his death in 1885,⁷⁵ even after the appointment of Cabot and Chandler.

In a further report of February 1878, Billings urged the Trustees finally to make a decision about the detail of the heating and ventilation.⁷⁶ The way that he presented his ideas demonstrated clearly his method as well as his aim that the Johns Hopkins would set out the best way of achieving good ventilation. In this respect, Billings suggested that the work would be particularly valuable for less well-endowed hospitals; the Hopkins bequest allowed the kind of experiment that less well-resourced institutions simply could not carry out. Billings’ report touched on heating, though tentatively, for here he felt that the data was still lacking. However, his consideration of ventilation was based on more concrete evidence. He began with discussion of the amount of air that was required to keep the atmosphere fresh and safe. He continued by outlining his views on inlet and outlet locations, referring not only to the literature but also what he had seen in the USA and Germany. Particular attention was given to what Billings termed ‘positive data’, gathered by monitoring existing hospital buildings in Washington and Boston. These experiments had been carried out at Billings’ request.

The Washington hospital was a brick, multi-storey structure with low temperature hot water heating.⁷ It had heating coils in brick chambers in the basement, at the sides between the windows. At the point of entrance of the supply pipe to each coil, a valve allowed the amount of air to be regulated. Air could be admitted to the wards at either ceiling or floor level; floor level was preferred. The particular interest of this hospital for Billings was that it offered a comparison between natural ventilation, which was used in summer, and both propulsion and aspiration. Air was drawn in through a single vertical airshaft at some distance from the buildings and was then ducted below the hospital into the wards. Although air could be exhausted via numerous heated ducts that led to two principal exhaust stacks, a 6 horse power fan could also be used to drive air through the building – either to cool it in hot weather or to blow through a rapid air change. The fan was run under Billings' instructions at different rates for experimental purposes. A year's worth of data was collected; the conclusion was that the heating arrangements worked well while the blow-through was also deemed successful.

Meanwhile in the case of the Boston example,⁸ Billings was able to report on 'a series of experiments and observations' made under his direction in a one-storey ward of 94 feet (28 m) long by 26 1/3 feet (8 m) by 20 feet (6.1 m) high – a type that resonated especially closely with what was proposed for the Johns Hopkins. These wards had seven windows per side – like those at the Johns Hopkins – while the ground floor was wholly devoted to ventilation. The report noted that only the hospital engineer had the right of entry to this space; he alone could adjust the equipment. Air entered the ward solely through openings in the ground-floor walls. It could either pass unheated into the ward, or be passed to a varying degree over steam coils. Exhaust was at ceiling level. Here the results suggested that the air was not mixing well and it was reported that a smoke test was to be carried out to determine more exactly the air movement.

Billings continued with a discussion of the ventilation of the House of Representatives and by calling for details of yet more hospitals before

concluding his review by noting the fundamental issues that he saw in hospital ventilation:⁷⁹

1. Poor arrangement of the buildings
2. Insufficient flue sizing
3. Improper arrangement of flues to secure constant and uniform dilution
4. That the power of the wind was forgotten and so systems dealt only with the wind from one direction
5. Unwillingness or inability to use the equipment provided by architect and engineer, either to save energy or through 'carelessness'
6. What Billings called 'want of intelligent, careful and continuous supervision'

Billings suggested that the ideal was an automatic system, but in this respect he was critical of the blowers that were then commercially available because he believed them too noisy.

Billings then outlined a final proposal, which featured three different ward types.⁸⁰ The first was a linear Nightingale-like ward; the second was a version of Folsom's centralised layout, transformed into an octagon; and the third was an isolation ward arranged as a series of individual rooms. Isolation here meant not so much those patients with particularly infectious conditions as those whose conditions meant that they themselves were deemed 'offensive', perhaps particularly malodorous. Serving all the wards were central boilers from which pipes were connected to coils between the beds, which could be adjusted individually.

The linear Nightingale-type ward accommodated 24 beds in a space 99 feet 6 inches (30.3 m) by 27 feet 6 inches (8.3 m) and thus was slightly larger than that at Boston but narrower than Nightingale's preferred 30 feet (9.1 m) width. The wards were oriented east/west with a sun room to the south (**fig. 4**). Unlike Billings' 1875 scheme, which had allowed for the possibility of two-storeys of wards over the ventilation chamber, the realised version had wards at first floor level only with (as in 1875) the ground floor devoted to the heating and ventilation equipment. The strategy was more developed though not wholly unlike that previously proposed. Outside air was admitted to a duct within the external walls, with (as at Boston and as proposed by Folsom)

a lever controlling whether it was taken directly into the ward or diverted into the heater; the temperature of the incoming air could thus be reduced without compromising the quantity of air. Other ducts brought in air below the windows to reduce draughts. Meanwhile air was exhausted in two places, at ceiling level and floor level through grilles below the beds. The ceiling exhaust was to be used in hot weather only, or when a blow-through was needed. One of the wards had an additional fan, which could be used for blow-through or on particularly hot days to produce a cooling breeze, and all of the wards were designed to allow a fan to be retro-fitted. Similarly with an eye to the future, the wards were lit by gas but with the possibility of future electric lighting.

The isolation ward countered difficult cases with enhanced air-change rates (**fig. 2**). Each room was approximately 11 feet (3.3 m) by 13 feet (4 m) with double doors creating a quasi-air lock. Air entered in much the same way as the common ward, but in greater volume. An open fireplace offered radiant heat while there was also a double-sided cupboard for the commode, lined in metal to allow cleansing by flame and with its own ventilation exhaust. The central corridor was open at both ends. Three rooms had perforated floors, like Reid's House of Lords, with the intention being that the patient would lie in a constant current of air supplied through 5000 holes per room. Air was exhausted via the fume cupboard, the stack running alongside the chimney whose heat would have amplified its effect.

The octagon ward drew on Folsom's proposal; the idea had obviously also appealed to Niernsee.⁸¹ With two ward floors over the ground-level ventilation chamber (**fig. 5**), air was introduced into the wards at the perimeter and exhausted at the centre via upper and lower grilles on each face of the central duct. The duct was of complex arrangement, containing a boiler flue and accelerating coil, while a further pipe within it removed smoke from the ward fireplaces. Whilst (as has been noted) there were wider debates concerning the merits of centralised planning at this time, the reasons for its adoption were more prosaic: had a second row of wards been constructed, south of those which were built and symmetrical with them, a linear ward would have collided with the nurses' home (**fig. 1**). Whilst thus

perhaps accidental, the result, evocative of the antique Tower of the Winds at Athens,⁸² was highly appropriate in a symbolic sense given the emphasis on ventilation in the design of the Johns Hopkins.

Although the hospital's ventilation strategy was at once implicit in and generated by its architecture, like other examples of this period it required a degree of fine-tuning and adjustment in daily use for its effective operation (**fig. 6**).⁸³ The diagrams reveal that there were some forty-four controls on each ward governing the air inlet grilles and the direction of exhaust, that is, whether air was to be exhausted at floor or ceiling level. One wonders how quickly the staff felt confident in the use of these devices. It is surely no coincidence that the first month of the nurses' training courses was spent learning about ventilation and the air. The archives reveal that their first lecture was entitled 'Physical Properties of the Atmosphere'.⁸⁴ It was followed by sessions including 'Practical Methods for Studying Ventilation' and 'Demonstration of Different Plans of Ventilation, shown upon a model specially constructed for the purpose'. Only after six weeks did the nurses – evidently now equipped to operate the ventilation system – move on to subjects more usually associated with their vocation in a lecture on 'The digestive system'.

Thus far it has been suggested that both Billings and the Trustees adopted what could be termed an 'experimental' approach to the commission in seeking information before developing and realising a hypothesis. This approach continued after construction. Initial results of the building's performance in use were published in 1890 and expanded in a further report of 1891.⁸⁵ The study was carried out by Billings with Alexander Abbott. Abbott presented for the common and octagon wards (but sadly not the isolation ward) a year's worth of temperature and humidity data (**table 1**). He began by describing the operation of the building, noting that the ventilation could never be shut off; rather only the temperature of the incoming air could be altered by the nurses using a special key. The ceiling ventilators were usually kept closed but were opened on occasion as 'flushing' devices to reduce the temperatures within ten to fifteen minutes. Nurses recorded temperatures hourly using special proformas. The results revealed that winter average

temperatures remained remarkably consistent at around 70°F or 21°C, with the octagon wards (D & E) slightly cooler than the Nightingale-type wards F, G, and H.⁸⁶ Summer average internal temperatures were a little higher and in fact tended to track closely external average temperatures. This seems to be because the windows were left open during the day – an unhelpful move to twenty-first century eyes, as closed and shaded windows might have maintained lower internal temperatures. There was less variation between the ward types than in winter. Winter average airflow was measured at around 1.5 cu.ft. per second per bed; the figure dipped in the summer. For context, the isolation ward was intended to provide 2 cu.ft. per second per bed, with 4-8 cu.ft. per second per bed in the rooms with perforated floors. Comments were made on the humidity of the air, which was moistened with damp cloths. The observed data was compared with more qualitative impressions. It was noted that there was an ‘entire absence of organic impurity as detected by the senses’. Abbott regretted that the study was perhaps not as complete as might have been hoped. He had spent part of the year in Germany,⁸⁷ and one wonders if the colleagues he left behind were less diligent in their efforts. Nonetheless, he concluded that the reduced excess of relative humidity in January 1891 compared to February 1890 demonstrated ‘improvements in the methods of working this system’, which had come about ‘as our acquaintance with the proper manipulation of the apparatus becomes more and more intimate’ (**table 2**).⁸⁸ Abbott hoped to undertake further work, but the monitoring apparently ended when both Billings and Abbott left Baltimore during 1891.⁸⁹

‘As perfect as possible’

Billings cemented his position as an authority on environmental design by lecturing with Abbott at the University of Pennsylvania from 1891,⁹⁰ and with his book, *Ventilation and Heating*, which was published in 1893. This work confirmed his interest in gathering solid evidence on which to base architectural and engineering decisions. Billings wrote in the book that his criticism of hospitals was ‘not for the purpose of fault-finding’ but rather to make things ‘as perfect as possible’.⁹¹ In other words, perfection was an

attainable goal, and could be reached through careful analysis as well as practical experiment. Whether it was achieved, however, is a different matter. The relative crudeness of Abbott's statistics may disguise reality. Certainly the building may not have been operated as intended. Niernsee recorded of other examples in 1876 that ventilation valves were often 'left for days in the same position' regardless of conditions.⁹² Billings meanwhile concluded *Ventilation and Heating* by warning that those operating the heating and ventilation of public buildings must understand the system in their charge: 'an ignorant and careless engineer' was 'the most wasteful of all expenditures'.⁹³

As it turned out, the Billings-era buildings at the Johns Hopkins were relatively short-lived, with some being demolished in the 1920s and all the wards having disappeared by the 1960s. Today only the Administration Building survives and is seemingly devoid of any original ventilation or heating apparatus.⁹⁴ In some ways, the scheme was considered out of date within only a few years of completion as understandings of infection transmission continued to develop, with attention shifting increasingly from such 'architectural' matters as ventilation to more personal factors.⁹⁵ For example, it was in fact at the Johns Hopkins Hospital that the disposable sterile glove first came into use during the 1890s.⁹⁶ By 1902, it was reported that the new wards constructed for black patients were 'bright and cheery, though somewhat disfigured and made inconvenient for working purposes by a ventilating shaft in the centre of each.'⁹⁷ The visible presence of ventilation devices was evidently now thought to be at odds with efficient function. By the 1930s, hospitals were increasingly planned on more compact lines.⁹⁸ Indeed, even at the time of Billings' death there were some who considered his 'military' layout rather outdated.⁹⁹

Billings might not have been unduly perturbed by such remarks, however. In his quest for a hospital that was 'as perfect as possible', the Johns Hopkins represented a distillation of his understanding at a particular moment in time, based on American and European practice and realised with input from others in the expectation that the operation of the building would yield further insights. It contributed to an on-going, multidisciplinary and

international discourse on ventilation that encompassed not only publications but arguably also buildings themselves. Thus while his remarks at the hospital's opening appealed to the conventional image of architecture as body ('a hospital is a living organism [...] the stream of life which runs through it is constantly changing')¹⁰⁰ Billings also conceived the hospital in less anthropomorphic terms, suggesting in his first report to the Trustees that 'the building is but a tool'.¹⁰¹ The 'tool' in question would not only aid its patients' recovery, but would also generate a better understanding of ventilation. The dissemination of that understanding – the hospital 'contrived with a view to instructional purposes', to reprise the RIBA's phraseology – was intended to be as much a legacy of Johns Hopkins as the improved health of the local population. Billings pointed out that external temperatures in Baltimore ranged from 0 to 100°F,¹⁰² and thus the results would potentially have widespread application, in a range of climates.

Whereas commentators on hospital architecture had long struggled to justify the scale and magnificence of many of these buildings, seeing palatial luxury as something opposed to efficient patient care and a possible waste of money,¹⁰³ the architecture of the Johns Hopkins Hospital shaped its internal environment and so allowed the building to play its 'instructional' role; it was not merely indicative of status. Billings, earlier an advocate of austere temporary structures, was reconciled to the idea of monumentality on account of the hospital's didactic purpose.¹⁰⁴ The internal grilles and ducts, like the ventilation stacks that ranged along the roofs and the prominence of the hospital in print, meant that the invisible (though not imperceptible) movement of air was made highly visible as something which could breathe new life not only into patients but also restore the hospital as a building type.

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¹ Johns Hopkins, letter to Trustees, in *Hospital Plans: Five Essays Relating to the Design, Construction, Organization and Management of Hospitals, Contributed by their Authors for the Use of the Johns Hopkins Hospital, Baltimore* (New York, William Wood and Co., 1875), p. xv.

² Baltimore, The Alan Mason Chesney Medical Archives of the Johns Hopkins Medical Institutions (hereafter 'AMCMA'), Board of Trustees Minutes, 13 November 1874 and 9 November 1875.

³ *Hospital Plans*, p. vii.

⁴ See F.H. Garrison, *John Shaw Billings: a Memoir* (New York, Knickerbocker Press, 1915), and J.L. Cameron, 'Early contributions to the Johns Hopkins Hospital by the "other" surgeon: John Shaw Billings', *Annals of Surgery*, 234, no. 3 (2001), pp. 267-78 (online at <<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1422018/>>, accessed 18 December 2013).

⁵ AMCMA, Trustees' Minutes, 28 June 1876.

⁶ AMCMA, box 507703, J.S. Billings, 'Reports and Plans Relating to Construction and Organization', 2, 20 September 1876, p. 17; also 'Reports and Plans Relating to Construction and Organization', 3, 11 January 1877, p. 12.

⁷ AMCMA, box 507703, J.S. Billings, 'Reports and Plans Relating to Construction and Organization', 5, 12 February 1878, p. 75.

⁸ 'A tour in the United States', *RIBA Transactions*, 2nd ser., 7 (1890), pp. 377-78.

⁹ E.g. H. Schoenefeldt, 'Adapting glasshouses for human use: environmental experimentation in Paxton's designs for the 1851 Great Exhibition Building and the Crystal Palace, Sydenham', *Architectural History*, 54 (2011), pp. 233-73. For classic earlier studies, see S. Giedion, *Mechanization Takes Command: a Contribution to Anonymous History* (New York, Oxford University Press, 1948); R. Banham, *The Architecture of the Well-Tempered Environment* (London, Architectural Press, 1984). A broader view is evident in e.g. D. Hawkes, *Architecture and Climate: an Environmental History of British Architecture, 1600-2000* (London, Routledge, 2011).

¹⁰ G.H. Brieger, 'The original plans for the Johns Hopkins Hospital and their historical significance', *Bulletin of the History of Medicine*, 39 (1965) pp. 518-28; J.D. Thompson and G. Goldin, *The Hospital: a Social and Architectural History* (New Haven and London, Yale University Press), pp. 175-87.

¹¹ R. Bruegmann, 'Central heating and forced ventilation: origins and effects on architectural design', *JSAH*, 37, no. 3 (1978), pp. 143-60 (p. 153, n. 42).

¹² E.g. AMCMA, Drawing 6.23, elevations and plans of ventilating pipes, signed C.W. Newton. The name of the firm is given thus in AMCMA, box 507703, 'Report No. 5', p. 85, but is credited elsewhere as Bartlett Hayward.

¹³ The surviving Cabot and Chandler drawings are almost all of details: see e.g. AMCMA, Administration Bldg/ Arch.Drw 1.10, detail of base course. One assumes, therefore, that their task was to 'clothe' and execute the scheme, working in conjunction with the engineers who

presumably devised the detail of the apparatus. However, this aspect of the design history, and especially Niernsee's contribution, would repay further work.

¹⁴ L. Jardine, *On a Grand Scale: the Outstanding Career of Sir Christopher Wren* (London, HarperCollins, 2002), p. xiii.

¹⁵ W.S. Inman, *Report of the Committee of the House of Commons on Ventilation, Warming and Transmission of Sound* (London, John Weale, 1836), p. 8.

¹⁶ *Ibid.*, p. 76 and plate 3; D.B. Reid, *Illustrations of the Theory and Practice of Ventilation* (London, Longman, 1844), pp. 273-309 details the 'experiments' undertaken.

¹⁷ Reid, *Illustrations*, pp. 325-28.

¹⁸ Brueggemann, 'Central heating', pp. 151-52.

¹⁹ R. Briggs, *Report on the Ventilation of the Hall of Representatives and of the South Wing of the Capitol* (Philadelphia, Henry S. Ashmead, 1876).

²⁰ Schoenefeldt, 'Adapting glasshouses', *passim*.

²¹ C.A. Short, M. Cook, K.J. Lomas, 'Delivery and performance of a low-energy ventilation and cooling strategy', *Building Research and Information*, 37, no. 1 (2009), pp. 1-30.

²² F. King, reproduced in J.S. Billings, *Description of the Johns Hopkins Hospital* (Baltimore, Johns Hopkins Hospital, 1890), pp. 18-20.

²³ Garrison, *Billings*, p. 325.

²⁴ *Ibid.*, p. 14.

²⁵ See e.g. AMCMA, box 57, letter from Billings to S.C. Gilman on medical education, 28 March 1878.

²⁶ A. Forty, 'The modern hospital in England and France: the social and medical uses of architecture', in *Buildings and Society: Essays on the Social Development of the Built Environment*, ed. A.D. King (London, Routledge and Kegan Paul, 1980), pp. 61-93. See also A-M. Akehurst, '"The Body Natural as well as the Body Politic stands indebted": the hospital – foundation, funding and form', unpublished MS.

²⁷ C.I. Hammond, 'Reforming architecture, defending empire: Florence Nightingale and the pavilion hospital', *Studies in the Social Sciences*, 37, no. 1 (July 2005), pp. 1-24.

²⁸ A. Adams, *Architecture in the Family Way: Doctors, Houses and Women, 1870-1900* (Montreal and Kingston, McGill-Queens University Press, 1996), pp. 36-72.

²⁹ *Ibid.*, pp. 39-44.

³⁰ C. Stevenson, *Medicine and Magnificence: British Hospital and Asylum Architecture, 1660-1815* (New Haven and London, Yale University Press, 2000), pp. 166-67.

³¹ S.W. Goldhagen, 'Something to talk about: Modernism, discourse, style', *JSAH*, 64, no. 2 (2005), pp. 144-67.

³² Stevenson, *Medicine and Magnificence*, p. 5.

³³ Copy in AMCMA, Box 507698.

³⁴ Stevenson, *Medicine and Magnificence*, p. 4; T. Tredgold, *Principles of Warming and Ventilating Public Buildings* (London, Josiah Taylor, 1824), p. 180.

³⁵ Stevenson, *Medicine and Magnificence*, pp. 66-67, 155-70.

³⁶ F. Nightingale, *Notes on Hospitals* (London, J.W. Parker, 1859).

³⁷ Thompson and Goldin, *The Hospital*, pp. 118-69; J. Taylor, *The Architect and the Pavilion Hospital: Dialogue and Design Creativity in England, 1850-1914* (London, Leicester University Press, 1997); A. Adams, *Medicine By Design: the Architect and the Modern Hospital, 1893-1943* (Minneapolis, University of Minnesota Press, 2008), p. 9.

³⁸ E.g. T.C. Railton, *The Conditions Required from a Healthy House* (London, John Heywood, 1889), pp. 4-5.

³⁹ N. Tomes, *The Gospel of Germs: Men, Women and the Microbe in American Life* (Cambridge, Harvard University Press, 1998), p. 46.

⁴⁰ *Ibid.*, p. 58.

⁴¹ E.g. 'Fresh air and how to get it', *Builder*, 38 (1880), p. 87.

⁴² E.g. R. Boyle, *Experiments with Exhaust Ventilators at the Health Exhibition* (London, Robert Boyle, 1884), pp. 2-3.

⁴³ Thompson and Goldin, *The Hospital*, p. 189; Adams, *Medicine by Design*, p. 22.

⁴⁴ J.S. Billings, 'Hospital construction and organization', pp. 1-47 in *Hospital Plans: five essays relating to the construction, organization and management of hospitals, contributed by their authors for the use of the Johns Hopkins Hospital of Baltimore* (New York, William Wood and Co., 1875) (p. 15).

⁴⁵ For Abbott's knowledge of contemporary theory, see the records of the journal articles he presented in the *Bulletin of the Johns Hopkins Medical Institutions*, e.g. I, no. 1 (December 1889), p. 13.

⁴⁶ AMCMA, Trustees' Minutes, 11 May 1874, 13 November 1874.

- ⁴⁷ R.W. Chalfant and C. Belfoure, *Niernsee and Neilson: Architects of Baltimore* (Baltimore, Baltimore Architectural Federation, 2006), pp. 33 and 103.
- ⁴⁸ AMCMA, Trustees' Minutes, 13 November 1874.
- ⁴⁹ Ibid.
- ⁵⁰ King, letter to Trustees, in Billings, *Description*, pp. 18-20.
- ⁵¹ *Hospital Plans: Five Essays* (n. 1 above), of which the following descriptions are a summary.
- ⁵² J. Taylor, 'Circular hospital wards: Professor John Marshall's concept and its exploration by the architectural community in the 1880s', *Medical History*, 32, no. 4 (1988), pp. 426-48.
- ⁵³ AMCMA, drawing FOL 004 is a section of the scheme.
- ⁵⁴ J.S. Billings, *Ventilation and Heating* (New York, Engineering Record, 1893), p. 265.
- ⁵⁵ AMCMA, box 507698, J.R. Niernsee, 'Review of Hospital Plans', 1 January 1876.
- ⁵⁶ AMCMA, Trustees' Minutes, 28 June 1876.
- ⁵⁷ AMCMA, box 507703, J.S. Billings, 'Reports and Plans Relating to Construction and Organization', 1, 15 July 1876.
- ⁵⁸ AMCMA, box 507703, 'Report No. 2'.
- ⁵⁹ Chalfant and Belfoure, *Niernsee and Neilson*, pp. 32, 98.
- ⁶⁰ AMCMA, box 507703, 'Report No. 2', p. 11.
- ⁶¹ Billings had believed as much from the outset: see AMCMA, box 507703, 'Report No. 1'.
- ⁶² Brieger, 'Plans', p. 527.
- ⁶³ J.S. Billings, *A Report on Barracks and Hospitals, with Descriptions of Military Posts*, War Department, Surgeon General's Office: Circular No. 4 (Washington, Government Printing Office, 1870).
- ⁶⁴ Billings, *Report on Barracks and Hospitals*, p. VIII.
- ⁶⁵ Ibid., p. XX.
- ⁶⁶ Ibid., p. XXII.
- ⁶⁷ Ibid., p. 44.
- ⁶⁸ Ibid., p. XX, VII.
- ⁶⁹ Billings' letters to Nightingale are found in Z. Cope, 'John Shaw Billings, Florence Nightingale and the Johns Hopkins Hospital', *Medical History*, 1, no. 4 (1957), pp. 367-68. The archivists at the New York Public Library have not been able to find Nightingale's replies in Billings' papers (e-mail from Tal Naden, NYPL, to author, 2 May 2013), which may hint at Billings' response to their contents.
- ⁷⁰ E.g. AMCMA, box 504382, letter from Billings to Gilman, 11 November 1876, from Dresden.
- ⁷¹ AMCMA, box 507703, 'Report No. 3', p. 4.
- ⁷² AMCMA, Trustees' Minutes, 17 November 1877.
- ⁷³ AMCMA, box 507698, J.R. Niernsee, 'Review of Hospital Plans', 1 January 1876, pp. 39-43.
- ⁷⁴ Cited in D.R. Brown, 'The expanding role of the physician in defining nineteenth-century hospital architecture as evidenced in Dr John Shaw Billings' designs for Johns Hopkins Hospital (1876-1889)' (thesis [degree not stated], University of California, Berkeley, 1990), p. 10 (Copy archived at AMCMA).
- ⁷⁵ AMCMA, box 507607, Register of Visitors, entries for 1879, 1880, 1881, 1882, 1883, 1884.
- ⁷⁶ AMCMA, box 507703, 'Report No. 5', p. 1 and subsequent, of which the following is a summary.
- ⁷⁷ Ibid., pp. 21-31.
- ⁷⁸ Ibid., pp. 62-69.
- ⁷⁹ Ibid., pp. 73-79.
- ⁸⁰ Ibid., pp. 81-90; see also Billings, *Description*, pp. 35-36 and 73-96.
- ⁸¹ For Niernsee, see the appendix to *Hospital Plans*, pp. 335-37; see also Thompson and Goldin, *The Hospital*, p. 187.
- ⁸² P. Goad, 'Postwar and polygonal: special plans for Australian architecture, 1950-70', *Architectural Theory Review*, 15, no. 2 (2010), pp. 166-86 (p. 169).
- ⁸³ See e.g. J. Cook and T. Hinchcliffe, 'Designing the well-tempered institution of 1873', *Architectural Research Quarterly*, 1, no. 2 (Winter 1995), pp. 70-8 (p. 77).
- ⁸⁴ AMCMA, 'First report of the Superintendent of Johns Hopkins Hospital' [bound volume on open shelves], p. 7.
- ⁸⁵ Billings, *Description*, p. 75; A.C. Abbott, 'Report upon the Heating and Ventilation of the Johns Hopkins Hospital for the Year ending February 1st 1891', *Bulletin of the Johns Hopkins Medical Institutions* II, no. 16 (September 1891), pp. 129-31.
- ⁸⁶ *Public Ledger* reported on 8 May 1889 that the octagon wards were better ventilated, which may account for the difference. Clipping in AMCMA box 507699.
- ⁸⁷ AMCMA, Trustees' Minutes, 9 December 1890.
- ⁸⁸ Abbott, 'Report', pp. 130-31.

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- ⁸⁹ AMCMA, Executive Committee minutes, 28 April 1891.
- ⁹⁰ Garrison, *Billings*, pp. 278-80.
- ⁹¹ Billings, *Ventilation and Heating*, p. 307.
- ⁹² AMCMA, box 507698, review by Niernsee, p. 26.
- ⁹³ Billings, *Ventilation and Heating*, p. 495.
- ⁹⁴ Site visit by author, including cellars and attics, 6 February 2013.
- ⁹⁵ Tomes, *Gospel of Germs*, pp. 94-96.
- ⁹⁶ *Ibid.*, p. 103.
- ⁹⁷ AMCMA, Alumnae magazine, 1, no. 2 (March 1902), p. 43.
- ⁹⁸ Thompson and Goldin, *The Hospital*, pp. 187-203 and 215-16.
- ⁹⁹ Garrison, *Billings*, pp. 201-02.
- ¹⁰⁰ *Ibid.*, p. 205.
- ¹⁰¹ AMCMA, box 507703, 'Report No. 1', p. 6.
- ¹⁰² Billings, 'Hospital construction', p. 19.
- ¹⁰³ Stevenson, *Medicine and Magnificence*, pp. 6-8.
- ¹⁰⁴ AMCMA, box 504382, folder 10, C.E. Glatt, 'John Shaw Billings, the design of the Johns Hopkins Hospital, and the reform of American medical education', unpublished MS., p. 17.